Recovery of Nitrogen-15–Labeled Hairy Vetch and Fertilizer Applied to Corn

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ABSTRACT

Knowledge of the plant and soil recovery of nitrogen (N) from legume cover-crop residues and fertilizer is needed to improve corn N use efficiency. Nitrogen-15 labeled ammonium sulfate (AS) or hairy vetch (*Vicia villosa* Roth.) residues were applied at planting or AS at the six-leaf stage (sidedressing) to silage corn (*Zea mays* L.) grown in 38-cm–diameter by 60-cm–deep microplots containing a Jungdong loam (coarse loamy, mixed, mesic, Typic Udifluvents) in Suwon, Korea. The recovery of the labeled N sources was followed over 2 yr into the corn grain, stover, and the 0- to 15-cm depth of soil. Recovery of labeled N in the first-year corn was 32% of the planting-applied AS, 15% of planting-applied hairy vetch (HV) residues, and 46% of the sidedress AS. Conversely, the post-harvest soil contained more labeled N from the HV residues (38%) compared with planting AS (15%) or sidedress AS (14%). Total first-year recoveries of ^{15}N in crop plus soil after harvest were 47% for planting AS, 54% for HV residues, and 60% for sidedress AS, which are consistent for high summer rainfall (850 mm) climates. The second-year corn showed low availability of residual ^{15}N, although HV residues supplied about twice as much N (3.5%) as AS (1.5%). These results are consistent with other studies and show that AS is about twice as effective as legume residues in supplying N to a crop, whereas legume residues contribute about twice as much N to the soil.

M ODERN corn production requires management of N sources derived from fertilizers, crop residues, and manure. Nitrogen management systems that use inorganic fertilizer and organic sources, such as cover-crop residues, could combine the benefits of inexpensive fertilizer N with soil organic matter maintenance and C sequestration derived from the organic source (Legg and Meisinger, 1982). Developing corn N management systems that use a combination of inorganic and organic N requires knowledge of N recovery from each of these sources, but few studies have examined the simultaneous recoveries of N from fertilizer and organic sources.

A cover crop of hairy vetch has been shown to provide several benefits to corn production systems. Some of these benefits include adding 50 to 120 kg N ha^{-1} (Mitchell and Teel, 1977; Ebelhar et al., 1984; Decker et al., 1994; Clark et al., 1995, 1997a; Meisinger et al., 1991), providing a surface-residue mulch for reducing runoff and conserving soil moisture (Clark et al., 1995, 1997b; Ebelhar et al., 1984; Meisinger et al.,

1991), and the synergistic effect of the additional moisture interacting with additional N to produce a higher yield potential than fertilized corn without cover-crop residues (Decker et al., 1994). However, most of these results have been derived from conventional corn yield-response experiments and from soil moisture studies, with little direct data available on the recovery of N from cover-crop residues compared with fertilizer N.

Determining the fate and recovery of N in corn production systems using labeled N inputs has been an objective of agricultural research for several decades (Legg and Meisinger, 1982). Some common observations from corn studies on fine-texture soils receiving labeled fertilizer N within 4 wk of planting are that corn commonly recovers 30 to 55% of the ^{15}N in the above-ground crop with about 15 to 30% retained in the soil, mostly as organic N (Torbert et al., 1992; Timmons and Baker, 1992; Timmons and Cruse, 1990). Labeled legume residues have also been studied. Müller and Sundman (1988) reported ^{15}N releases from four different species of legume residues in Finland and found that 65 to 82% remained in the soil, whereas the succeeding barley (*Hordeum vulgare* L.) used only 17 to 24% of the legume ^{15}N. Varco et al. (1989) used ^{15}N-depleted HV residues to estimate legume contributions to corn grown under moldboard-plow and no-tillage culture in Kentucky and showed that corn recovered 32% and 20% of the HV-labeled N in moldboard-plow and no-tillage treatments, respectively. Cueto-Wong et al. (2001a) reported first-year sorghum (*Sorghum bicolor* [L.] Moench) ^{15}N recoveries from labeled HV residues of 19% in an irrigated sandy loam in New Mexico. The unrecovered ^{15}N in most labeled N studies is usually ascribed to nitrate leaching plus gaseous losses of denitrification and ammonia volatilization. However, the specific fate and recovery of the added ^{15}N in each individual study is a function of the N source, the rate and time of application, the soil and crop management practices, the soil type and water management, and the weather conditions of the study.

This research was undertaken to expand our understanding of the recovery of N derived from cover-crop residues compared with N supplied from conventional fertilizers in a corn-silage system receiving organic and inorganic N sources. The objectives were (i) to compare the crop and soil recovery of ^{15}N-labeled AS with ^{15}N-labeled HV residues using corn grown in field microplots, (ii) to determine the total recovery of the labeled N from each N source within the soil–plant system after 1 and 2 yr of corn growth, and (iii) to compare the results

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Abbreviations: AS, ammonium sulfate; DM, dry matter; HV, hairy vetch; LSD, least significant difference; RCB, randomized complete block; SD, sidedressed.

of this study with similar research to identify areas of consensus or disagreement.

MATERIALS AND METHODS

The experiment was conducted at the National Crop Experiment Station at Suwon, Korea (37°15′ N lat; 127° 55′ E long) in 1999 and 2000. The soil in the experiment is a well drained Jungdong loam (coarse loamy, mixed, mesic, Typic Udifluvents). Relevant physical and chemical properties are given in Table 1. The climate is classified in the Köppen system as Humid subtropical with distinct dry winters and hot summers and with a monsoonal rainfall pattern. Figure 1a summarizes these characteristics for the corn-growing season.

The microplots consisted of 36 PVC cylinders, each 38 cm in diameter by 60 cm long by 1.1 cm thick, that were pressed approximately 58 cm into the soil. Static weights were placed on top of each cylinder to press them into the soil and form the undisturbed soil microplots. The weights were lifted in place by a crane. The cylinders were pressed into the soil when the soil moisture was approximately 60% of field capacity. Extra water was applied as needed to avoid compaction. Minimal subsidence, amounting to less than 2 mm, was observed during installation in this coarse textured soil. The cylinders were open at the bottom to allow free drainage, and no attempt was made to collect leachate from the bottom of each microplot. Surface runoff was prevented by leaving a 2-cm edge of the cylinder protruding above the soil surface. These types of experimental microplots are commonly used for ^{15}N research (Legg and Meisinger, 1982; Hauck et al., 1994) to clearly define the soil–plant system. The surface 15 cm of soil was removed from the PVC cylinders, mixed, and returned.

The labeled HV residues were produced by growing HV from seed outdoors in large 20-L pots containing 22 kg of sand, similar to the method described by Jensen (1994). Pots were watered every few days with a minus-N nutrient solution with minimal solution inputs to minimize leaching. No leaching was observed outside the pots. Labeled AS containing 99 atom % ^{15}N was dissolved in water and applied in three equal split applications of 67 mg N per pot. Atmospheric N_2 fixation was allowed to proceed naturally, so the final atom % ^{15}N represents the ratio of the N absorbed from the labeled nutrient solution to the total accumulated N (labeled N plus unlabeled N from fixation). After 17 wk of growth, the aboveground crop and the roots were harvested at the flower initiation stage and air-dried at room temperature. The final vetch residues were prepared by cutting the top growth and roots into approximately 5-cm lengths, mixing the tops and roots together, and weighing out the appropriate quantities of residues for addition to the microplots. The HV residues were stored in a

freezer until field application. The HV total N content and atom % ^{15}N were determined on dried finely ground samples by isotope ratio mass spectrometry as described below. The HV residues contained 33.8 g N kg^{-1}, had a C/N ratio of 14:1, and contained 2.91 atom % ^{15}N. The large dilution of the nutrient solution ^{15}N with natural abundance atmospheric N indicates that about 97% of the HV total N came from N_2 fixation.

Treatment and Experimental Design

The treatment design contained three pre-plant N management strategies as primary variables plus two subtreatments within each strategy to estimate the recoveries of the pre-plant N and sidedress N. The primary treatments (Table 2) compared pre-plant N supplied from AS fertilizer (coded FN) at 13.3 g N m^{-2} (N rate code N2) with N supplied from HV at 13.3 g N m^{-2} (coded HVx1.0) or HV at 20.0 g N m^{-2} (coded HVx1.5). All treatments received 6.7 g N m^{-2} (N rate code N1) from sidedressed (SD) ammonium sulfate. The two subtreatments, nested within each primary treatment (Table 2), used ^{15}N labeling of the pre-plant N or the sidedress N to provide direct estimates of labeled N recovery from these sources. This treatment design allowed separate tracing of the labeled N sources applied at planting plus tracing of the sidedress N for each pre-plant N management strategy, and resulted in six treatments per replicate (i.e., the six subtreatments).

The experimental design was a randomized complete block (RCB) with six replicates. Each of the six subtreatments (Table 2) was randomly assigned to a microplot within each replicate, producing an RCB with 36 microplots. The results and discussion in this paper use the primary-treatment codes of Table 2 when referring to nonlabeled data (e.g., crop yields) or when combining the results from the nested subtreatments into a comparison of primary treatments. The subtreatment codes of Table 2 are used when discussing isotope data (e.g., crop recovery of ^{15}N from planting or sidedress applications).

First-Year Methods

The microplots were managed to emulate silage corn production with moldboard plow tillage by hand spading the microplots to 15 cm before planting. This primary tillage was used to thoroughly mix and incorporate the pre-plant AS fertilizer or HV residues and the P and K fertilizers that were supplied according to soil analysis (Table 1) from 6.6 g P m^{-2} of fused phosphate (9% P) and 12.5 g K m^{-2} from potassium chloride. The tilled soil was raked and left unplanted for 10 d. Planting occurred on 25 Apr. 1999 by seeding two kernels of 115-d-maturity corn (Pioneer 3394). After germination, corn populations were thinned to one plant per microplot at the

Table 1. Physical and chemical characteristics of the Jungdong loam soil at the National Experimental Station in Suwon, Korea.

Soil depth	Soil texture, U.S. classification†			Soil bulk density‡	pH water (1:5)§	Soil organic matter	Soil total N#	Available soil P††	CEC‡‡
	Sand	Clay	Texture						
cm	—— % ——			g cm^{-3}		g kg^{-1}	g N kg^{-1}	mg P kg^{-1}	cmol$_c$ kg^{-1}
0–20	50	9	loam	1.28	5.2	16.0	0.8	76	8.1
20–40	56	11	sandy loam	1.49	5.3	14.9	0.7	60	8.0
40–60	62	9	sandy loam	—	5.4	6.0	0.4	10	4.6

† Sand fraction determined by sieving; clay fraction determined by hydrometer (Nat. Inst. Agric. Sci., 2000).
‡ Bulk density determined by coring soil adjacent to microplots after harvest as described in Materials and Methods.
§ pH in 1:5 suspension of soil/water measured after 1 h (Nat. Inst. Agric. Sci., 2000).
¶ Organic matter by Walkley-Black, 1 N dichromate oxidation in concentrated sulfuric acid and titration of excess dichromate with ferrous ammonium sulfate (Nat. Inst. Agric. Sci., 2000).
# Kjeldahl digestion with concentrated sulfuric acid with copper catalyst, distillation, and titration (Bremner and Mulvaney, 1982).
†† Available P by Bray-1, 1 N NH$_4$F in 0.5 N HCl (Olsen and Sommers, 1982).
‡‡ Cation exchange capacity by ammonium acetate at pH 7 and distillation (Nat. Inst. Agric. Sci., 2000).
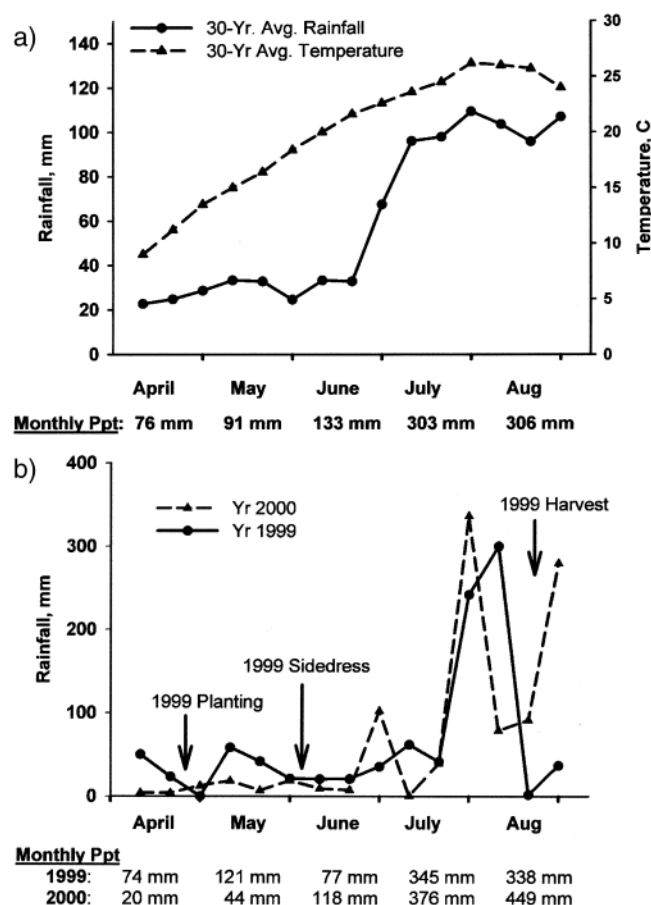
Fig. 1. Climate and weather data for Suwon Korea. (a) Long-term 30-yr climate data for 10-d intervals throughout the growing season. Total monthly precipitation is listed below each month. (b) Rainfall data at National Crop Experiment Station for 10-d intervals in 1999 (solid line) and 2000 (dashed line). Dates of 1999 agronomic operations and monthly total rainfalls are listed below each month.

aboveground crop into an ear and stover portion. The ear and chopped stover were dried at 65°C, followed by shelling of the grain from the cob. The cob was then combined with the stover. The dry grain and dried stover plus cob were weighed to determine dry matter (DM) yield. Dried grain and stover were ground in a Willey mill through a 1-mm screen and reduced to a fine powder (< 0.15 mm) in a vibrating ball mill (Heiko model TI-100).

Soil samples from the surface 15 cm of soil were collected after corn harvest by compositing 10 2.3-cm–diameter cores from each microplot. The soil was sampled to 15 cm because this was the depth of tillage and the zone with greatest root density. Deeper soil samples were not collected to avoid formation of preferential flow channels that could ruin the microplots for the second year of this study and for future studies. The composite soil sample was mixed, spread in a thin layer, and dried at room temperature (about 23°C) for several days. The dried soil was sieved through a 2-mm mesh screen and finely ground to a powder in the Heiko mill for later analysis. The bulk density of the surface soil in each microplot was estimated after harvest by collecting an undisturbed core measuring 7.3 cm in diameter by 7.6 cm high (318 cm^3) from the center of the 0- to 15-cm layer, which was dried at 105°C, sieved, and weighed to estimate bulk density.

Chemical analyses were performed on the finely ground samples of corn grain, stover, and surface soil. The total N analysis was performed by Dumas combustion as part of the ^{15}N analysis on an isotope ratio mass spectrometer (Micromass model Isoprime-EA). The C analysis on the HV residues was performed on a LECO model CNS2000 analyzer. The fraction of the plant (or soil) N derived from a labeled N source was calculated from the isotope dilution formulae (Hauck et al., 1994) by dividing the atom % excess ^{15}N in the N component (e.g., corn grain, stover, or soil) by the atom % excess of the N source (e.g., HV or AS). The quantity of labeled N in the mature corn or soil was calculated by multiplying the above fraction of N derived from the labeled source by the component's total N content (DM × total N concentration). The percent recovery of labeled N was calculated by dividing the quantity of labeled N by the rate of ^{15}N applied (Hauck et al., 1994).

Second-Year Methods

The second year of the study was a residual study to document the recovery of the previous year's addition of labeled N. The corn stover residues from the first year's crop were not returned to the microplots to simulate a corn–silage management system. The crop cultural practices were the same as in 1999, with corn planted on 3 May 2000, sidedress N applied on 26 June 2000, and corn harvested on 24 Aug. 2000. Nitrogen

three-leaf stage to ensure a uniform stand of healthy plants. The thinned plant was left in each microplot to recycle any ^{15}N taken up. The area between microplots was cropped to the same corn variety at a density similar to the density in the microplots. Sidedress AS, with 5.2 atom % ^{15}N or without labeled N as per Table 2, was applied at the corn six-leaf stage on 15 June 1999 by broadcasting and shallow raking into the surface soil. Corn was hand harvested at the black-layer stage on 20 Aug. 1999 by cutting at the soil surface and dividing the

Table 2. Treatment design for comparing three pre-plant N management strategies with N from fertilizer (FN + SD) or hairy vetch residues at 13.3 g N m^{-2} (HVx1.0 + SD) or from a high rate of hairy vetch (HVx1.5 + SD) residues. The subtreatments describe the deployment of labeled N sources for tracing the recovery of N from the pre-planting or sidedress N applications for each N management strategy.

		Subtreatment description				Total N added
		Preplant		Sidedress		
Preplant treatment code†	Subtreatment code‡	N source†	g N m^{-2}	N source†	g N m^{-2}	g N m^{-2}
FN + SD	AS-^{15}N2 + AS-N1	AS w/^{15}N	13.3	AS	6.7	20.0
	AS-N2 + AS-^{15}N1	AS	13.3	AS w/^{15}N	6.7	20.0
HVx 1.0 + SD	HV-^{15}N2 + AS-N1	HV w/^{15}N	13.3	AS	6.7	20.0
	HV-N2 + AS-^{15}N1	HV	13.3	AS w/^{15}N	6.7	20.0
HVx 1.5 + SD	HV-^{15}N3 + AS-N1	HV w/^{15}N	20.0	AS	6.7	26.7
	HV-N3 + AS–^{15}N1	HV	20.0	AS w/^{15}N	6.7	26.7

† FN is fertilizer N at 13.3 g N m^{-2}; SD is sidedress N at 6.7 g N m^{-2}; HVx1.0 is hairy vetch N at 13.3 g N m^{-2}; HVx1.5 is hairy vetch at 20.0 g N m^{-2}.
‡ AS is ammonium sulfate with 5.2 atom % ^{15}N or unlabeled natural abundance; HV is hairy vetch with 2.91 atom % ^{15}N or unlabeled natural abundance; N1, N2, and N3 are nitrogen rates of 6.7, 13.3, and 20.0 g N m^{-2}, respectively.

fertilization used unlabeled urea N, which was incorporated into all microplots at 10.0 g N m^{-2} at corn planting and side-dressed with 5.0 g N m^{-2} at the six-leaf stage. A somewhat lower rate of N was applied the second year to provide a moderate corn N stress to encourage efficient crop recovery of available ^{15}N from the previous year. Phosphorus and K applications and all other agronomic methods were the same as the previous year. Plant and soil sampling and the preparation and analysis of total N and labeled N data were the same as the previous year.

Statistical Analysis and Data Summary

Statistical analyses used the General Linear Models Procedure of the Statistical Analysis System (SAS Institute, 2000) with an RCB design considering the replicates and the treatments as fixed effects. The nonlabeled data (e.g., yield, total N uptake) contained the three primary treatments (Table 2) in each replicate, but each primary treatment was applied to two microplots within each replicate (the two subtreatments). These two microplots were averaged within each replicate, and the statistics were conducted on the within-replicate means using an RCB analysis with six replicates and 18 df total. Analysis of the labeled N data (e.g., grain ^{15}N uptake) used the six individual microplots (the six subtreatments of Table 2) within each replicate in a six-replicate RCB analysis and 36 df total. Treatment analyses are based on a protected least significant difference (LSD) approach, in which an LSD value was calculated only if the general treatment F test was significant at a probability of ≤ 0.05 (Snedecor and Cochran, 1987). The LSD values are listed in the respective tables to numerically document the uncertainty of each variable and to allow calculation of the associated variances, which are useful for designing future studies.

RESULTS

First-Year Nonlabeled Data

The humid subtropical climate of the site (Fig. 1a) is marked by a distinct summer wet season that has average monthly rainfalls of about 300 mm. Corn planting is scheduled to synchronize crop water use with summer rainfall, but the high rainfall can also affect crop N recovery due to possible leaching or denitrification. The 1999 weather was consistent with the long-term patterns: Temperatures averaged within 1°C of the long-term averages (data not shown), and monthly rainfall totals (Fig. 1b) were somewhat above the long-term monthly average (Fig. 1a). There were two distinct periods of high rainfall (> 250 mm over 10 d) in 1999 (Fig. 1b, solid line) that encouraged N loss from the coarse textured soil. This variable high rainfall pattern is typical of the summer monsoonal rainy season of the region.

The 1999 corn DM data (Table 3) show that corn grain yields were not different among the three primary treatments, but total whole-plant DM production was significantly higher for microplots receiving the high rate of HV due to greater production of stover. The lower rate of HV residues (HVx1.0 + SD) used in this study was approximately 390 g DM m^{-2}, which represents the residues from an average winter cover crop under Korean conditions (Seo et al., 2000a) and also under U.S. conditions (Clark et al., 1995; Decker et al., 1994; Wagger, 1989; Sarrantonio and Scott, 1988). The

Table 3. Corn dry matter yield, total N concentration, and total N yield for nonlabeled N data in 1999.

Primary treatment code†	Dry matter yield	Total N conc.	Total N yield
	g m^{-2}	g kg^{-1}	g N m^{-2}
		Corn grain	
FN + SD	760	11.0	8.4
HVx1.0 + SD	700	9.1	6.4
HVx1.5 + SD	760	10.1	7.7
LSD ($P < 0.05$)	NS	1.2	0.6
		Corn stover	
FN + SD	1570	4.3	6.7
HVx1.0 + SD	1561	3.4	5.2
HVx1.5 + SD	1711	3.6	6.2
LSD ($P < 0.05$)	115	0.6	0.9
		Corn whole plant	
FN + SD	2330	6.4	15.1
HVx1.0 + SD	2261	5.1	11.6
HVx1.5 + SD	2471	5.6	13.8
LSD ($P < 0.05$)	159	0.6	1.2

† FN is fertilizer N at 13.3 g N m^{-2}; SD is sidedress N at 6.7 g N m^{-2}; HVx1.0 is hairy vetch N at 13.3 g N m^{-2}; HVx1.5 is hairy vetch at 20.0 g N m^{-2}.

high rate of HV residues (HVx1.5 + SD) was approximately 590 g DM m^{-2} and represents a very good winter cover crop (Clark et al., 1995; Decker et al., 1994; Wagger, 1989; Sarrantonio and Scott, 1988) under Korean and U.S. conditions. The nonlabeled N data (Table 3) show statistically higher N concentrations for the whole plant in the fertilizer N treatment (FN + SD) compared with the HV treatments and no statistical difference in N concentrations between the two HV treatments. The higher N concentrations in the fertilizer treatment whole plant were the result of higher N concentrations in the stover. The corn whole plant total N yield was statistically highest for the fertilizer treatment, followed by the high-rate HV treatment and the low-rate HV treatment. These differences in whole-plant N yield are accounted for mainly by differences in grain N accumulation (Table 3), where the FN + SD treatment had significantly higher grain N yield compared with the other treatments.

The corn grain DM yields, total DM yields, and total N uptake data of Table 3 agree with results from conventional N response experiments in Korea (Seo et al., 2000b, 2001) and in the USA (Decker et al., 1994; Clark et al., 1995; Varco et al., 1989; Ebelhar et al., 1984; Sarrantonio and Scott, 1988), where comparisons of HV residues vs. fertilizer N at the same N rate generally produced lower yields and lower N uptakes with the vetch residues. The high rate of HV (HVx1.5 + SD), receiving a total of 26.7 g N m^{-2}, produced statistically higher stover DM yields than the fertilized treatment (FN + SD) receiving a total of 20 g N m^{-2}, but the total N uptake of the high-vetch treatment was still below the fertilizer treatment. Thus, the N availability to the crop from pre-plant fertilizer was higher than N availability from HV residues, although grain DM and total DM were similar.

First-Year Labeled Nitrogen Data

Crop Data

The percentage recovery of the pre-plant labeled N in the corn (Table 4) shows statistically significant differ-

ences among planting treatments, with the recovery of the HV ^{15}N being about one half that from AS in the corn grain, in the corn stover, and in the whole plant. In contrast, the percentage recovery of the SD-labeled N was similar for all pre-planting treatments, averaging about 46% in the whole plant (Table 4). The similar recoveries of SD ^{15}N can be attributed to the 7-wk time interval between planting and sidedressing. This 7-wk period allowed the HV residues to react with the soil before the SD nitrogen was applied. The residue bag incubation studies of Seo et al. (1998) reported that total N declined 90% within the bag during a 7-wk incubation with soil-incorporated residues. Other field soil core incubation studies (Varco et al., 1993) reported that 90% of the ^{15}N was transformed or released from labeled HV residues during a 7-wk incubation in soil, whereas Stute and Posner (1995) reported a 70% decline in HV total N from nylon bags incorporated within the soil over 6 wk. Therefore, the labeled N crop data show that corn fertilized with pre-plant labeled AS recovered about twice as much ^{15}N as from labeled HV residues, whereas ^{15}N applied at sidedressing was not affected by the pre-plant N treatments.

Table 4 illustrates the importance of fertilizer N timing: Whole-plant ^{15}N recovery from the pre-plant AS was 32%, whereas the sidedressed AS produced a 48% recovery. Thus, corn N use efficiency can be improved by timing N applications in phase with crop demand, especially on a coarse textured soil in a high-rainfall environment. Field experiments in the USA by Bigeriego et al. (1979) and Russelle et al. (1981) have reported a 5 to 18% increase in crop N recovery of labeled N for sidedress vs. planting applications on an irrigated silty clay loam Mollisol containing 2 g N kg^{-1}. Non-irrigated ^{15}N experiments in Minnesota (Jokela and Randall, 1997) on a well drained silt loam soil containing 1.3 g N kg^{-1} also reported 2-yr average increases of 10% in whole-plant recovery of ^{15}N for sidedress vs. planting applications.

Table 4. First-year recovery of labeled N from fertilizer or hairy vetch in silage corn, in soil, and total plant plus soil ^{15}N recovery.

| | ^{15}N recovered in corn | | |
Subtreatment code†	Grain	Stover	Whole plant	^{15}N in soil at end of season, 0–15 cm	Total ^{15}N recovery
	%				
	^{15}N applied at pre-planting				
AS-^{15}N2 + AS-N1	19	13	32	15	47
HV-^{15}N2 + AS-N1	9	7	15	38	54
HV-^{15}N3 + AS-N1	9	7	17	41	57
	^{15}N applied at sidedressing				
AS-N2 + AS-^{15}N1	24	24	48	14	62
HV-N2 + AS-^{15}N1	23	20	43	14	57
HV-N3 + AS-^{15}N1	26	21	46	13	59
LSD (P < 0.05)	3	3	4	4	5

† First hyphenated code before "+" refers to the pre-plant treatment; second hyphenated code after "+" refers to sidedress N treatment. AS is ammonium sulfate with 5.2 atom % ^{15}N or unlabeled natural abundance; HV is hairy vetch with 2.91 atom % ^{15}N or unlabeled natural abundance; and N1, N2, and N3 are nitrogen rates of 6.7, 13.3, and 20.0 g N m^{-2}, respectively (see Table 2 for detailed treatment description).

Soil Data

The percent recovery of labeled N in the surface 15 cm of soil (zone of incorporation) shows significantly higher ($P < 0.05$) recoveries for HV residues compared with N from AS (Table 4) at the end of the growing season. Labeled N recovery in the soil averaged about 40% for vetch residues, whereas the comparable value from AS was only 15%. Soil analyses showed that the soil-labeled N was present in organic forms and not as ammonium or nitrate N (data not shown). This study did not monitor labeled soil N forms (e.g., NH_4–N, NO_3–N, biomass N, total N in identifiable residues) throughout the growing season and therefore cannot identify the cause for the greater recovery of HV ^{15}N in the organic N pool. However, it is common knowledge that the increased biological activity associated with the rapid breakdown of low C/N ratio residues can provide a sink for labeled N from the inorganic N pool or from simple organic forms of N (e.g., amino acids, amino sugars). Varco et al. (1993) reported that immobilization of added ^{15}N was consistently greater from HV residues than fertilizer, which they attributed to the close association of the C and the N in the HV residues compared with inorganic fertilizer N, which does not contain C. Thus, the soil ^{15}N data show that N originating from HV residues is more likely to be recovered in soil organic N than N originating from AS.

Total Recovery Data

The total recoveries of pre-plant applications of ^{15}N in the soil plus the whole-plant (Table 4) show statistically ($P < 0.05$) lower recoveries for AS applied at planting (47%) followed by the low rate of HV (54%), with no significant difference between the two HV treatments. The total recovery of the sidedress AS was 15% higher than the AS applied at planting (62% vs. 47%), with most of this difference accounted for in greater plant recovery for the sidedress N. The 54% total recovery of HV ^{15}N in this study is consistent with the 59% total recovery reported by Cueto-Wong et al. (2001a) on an irrigated sandy loam soil. The unrecovered ^{15}N varied from a 53% loss for planting AS (AS-^{15}N2 + AS-N1) to a 38% loss for sidedress AS (AS-N2 + AS-^{15}N1), with HV treatments averaging 43% unrecovered. These losses are not uncommon (Legg and Meisinger, 1982) for corn grown with about 850 mm of growing season precipitation (Fig. 1b), especially with a summer monsoon rainfall pattern on a freely draining soil. We postulate that the majority of the unrecovered N can be attributed to leaching on this coarse-textured soil, although denitrification likely contributed to a portion of the losses.

Nitrogen Sources Used by Corn and Sources of Nitrogen Recovered in the Soil

Corn in this study used N from the soil, from planting applied fertilizer or cover-crop residue N, and from sidedress fertilizer N. Figure 2 summarizes the N sources recovered in the corn and the soil for the three pre-

planting strategies (primary treatments of Table 2), which were derived from the total N uptake date (Table 3) and the ^{15}N recovery data (Table 4) for the pre-planting and sidedress N applications (multiplying the percent recovery by the respective N rate). Figure 2 shows that the largest source of N for the corn was from unlabeled soil N sources, amounting to 6.7 to 7.5 g N m^{-2}, which is about 1.7% of the total N in the surface 40 cm of soil and is within the normal range (1–3%) expected from mineralization of organic N (Bremner, 1965; Broadbent, 1984). Soil N made up an average of 54% of the corn total N uptake for the three pre-planting treatments, with no statistically significant differences among them. Fertilizer N applied pre-plant (FN + SD) contributed about 4.3 g N m^{-2}, which was 29% of the corn total N uptake of that treatment, whereas the same N rate of HV (HVx1.0 + SD) contributed only 2.0 g N m^{-2}, amounting to 18% of the corn total N uptake. The sidedress N supplied similar quantities of N (about 3 g N m^{-2}) to each of the three pre-plant treatments, which accounted for an average of 22% of the total corn N uptake.

The sources of N returned to the soil N pool (last two bars of each pre-plant treatment in Fig. 2) were largest for N applied at planting from HV residues. Pre-plant AS (FN + SD) contributed about 2 g N m^{-2} to the soil N pool, whereas the corresponding N rate from HV (HVx1.0 + SD) contributed 5 g N m^{-2} and the high-rate of HV (HVx1.5 + SD) contributed 8 g N m^{-2}. Figure 2 illustrates that N added in HV residues is more

N Sources Recovered in Corn and Soil

Legend:
- Corn N derived from Soil
- Corn N derived from Pre-plant [15]N Application
- Corn N derived from Sidedress [15]N Application
- Soil N derived from Pre-plant [15]N Application
- Soil N derived from Sidedress [15]N Application

Fig. 2. **Recovery of N sources at the end of the growing season in corn and in the soil (0–15 cm) for three N management strategies using 13.3 g N m^{-2} fertilizer N at planting plus sidedress N (FN + SD), 13.3 g N m^{-2} hairy vetch N at planting plus sidedress fertilizer (HVx1.0 + SD), and 20 g N m^{-2} hairy vetch N at planting plus sidedress fertilizer (HVx1.5 + SD). Detailed descriptions of the main treatments are given in Table 2.**

likely to be recovered as soil organic N and thus is more likely to conserve soil organic N than N applied as AS. Nitrogen applied at sidedressing contributed the least to the soil N pool, averaging only 1 g N m^{-2}, because more sidedress N was used by the crop (Table 4). The low soil recovery and high plant recovery of the sidedress N can likely be attributed to rapid crop use with an accompanying low interaction with the soil N cycle. This hypothesis was also proposed by Jokela and Randall (1997) to interpret the greater crop recovery of sidedress N in their field study.

These crop and soil data support the generalization that a silage–corn N management system based on fertilizer N (FN + SD) is more effective at supplying N to the crop with secondary contributions to the soil, whereas a system using HV residues plus sidedress N retains more N in the soil components with secondary contributions to the crop. By combining fertilizer N and cover-crop N sources into an integrated organic-plus-inorganic N management system, one can realize the positive benefits of each source, with fertilizer providing the major nutritional needs of the crop and cover crop residues contributing more to maintaining soil N resources.

The total ^{15}N recovery (plant plus soil) of all labeled N inputs (pre-plant N plus sidedress N) for the three N management strategies studied was 52% of the labeled N for the fertilizer-based (FN + SD) system, 54% for the low-rate HV system (HVx1.0 + SD), and 58% for the high-rate HV system (HVx1.5 + SD). The ^{15}N recovery from the high-rate HV treatment was significantly different from the other two treatments due in large part to the larger recovery of ^{15}N in the soil. The N not recovered for the three pre-plant treatments varied from 42 to 48% and represents the combined N lost to leaching, denitrification, and any N contained in the soil below the 15-cm sample depth.

Second-Year Data

Nonlabeled Nitrogen Data

The nonlabeled corn production data (DM, N concentration, and total N uptake) were not statistically affected by any of the previous-year treatments. Second-year corn growth was good, with average grain DM yields of 864 g m^{-2}, which produced an average grain N harvest of 7.3 g N m^{-2} (data not shown). These values are consistent with the corn grain data during the first year (Table 3). Whole-plant DM yields averaged 2390 g m^{-2}, accounting for an average total N uptake of 13.5 g N m^{-2} (data not shown), which is also consistent with the whole-plant data of Table 3.

Labeled Nitrogen Data

The ^{15}N data for the second-year crop (Table 5) show only small N uptakes of the original labeled N retained in the soil after the first-year crop. The residual ^{15}N consisted of the labeled organic N measured in the 0- to 15-cm depth of soil sampled at the end of the first year's study (Table 4) plus any labeled N that was contained in the 15- to 60-cm depth of the microplots. The HV
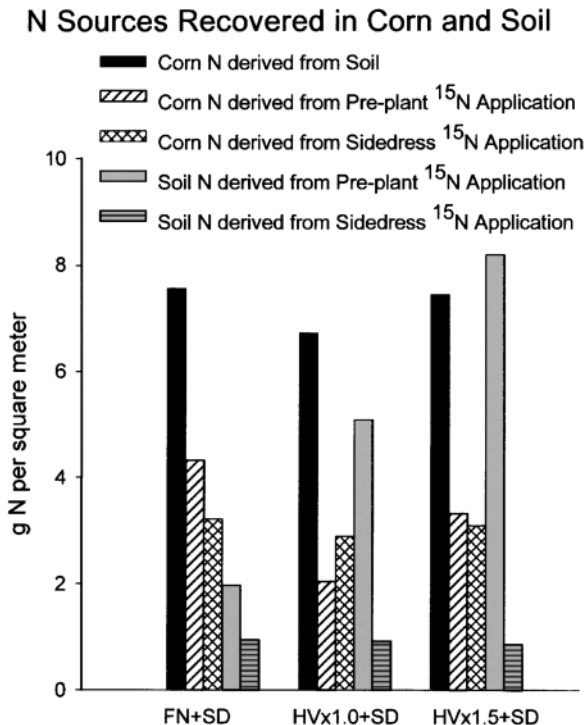
Table 5. Second-year recovery of residual labeled N from applications of fertilizer or hairy vetch in silage corn, in soil, and total ^{15}N recovery.

Subtreatment code†	^{15}N recovered in corn			^{15}N in soil at end of season, 0–15 cm	Total ^{15}N recovery
	Grain	Stover	Whole plant		
				%	
	^{15}N applied at pre-planting				
AS-^{15}N2 + AS-N1	0.9	0.7	1.6	14	16
HV-^{15}N2 + AS-N1	2.0	1.5	3.5	39	42
HV-^{15}N3 + AS-N1	2.0	1.4	3.4	35	39
	^{15}N applied at sidedressing				
AS-N2 + AS-^{15}N1	0.9	0.7	1.6	13	15
HV-N2 + AS-^{15}N1	0.8	0.6	1.4	15	17
HV-N3 + AS-^{15}N1	0.8	0.7	1.5	15	16
LSD ($P < 0.05$)	0.3	0.2	0.3	3	3

† First hyphenated code before "+" refers to the pre-plant treatment; second hyphenated code after "+" refers to sidedress N treatment. AS is ammonium sulfate with 5.2 atom % ^{15}N or unlabeled natural abundance; HV is hairy vetch with 2.91 atom % ^{15}N or unlabeled natural abundance; and N1, N2, and N3 are nitrogen rates of 6.7, 13.3, and 20.0 g N m^{-2}, respectively (see Table 2 for detailed treatment description).

sources contributed about twice as much residual N to the second-year corn as the AS sources (about 3.5% for HV compared with about 1.5% for AS). This is consistent with the fact that the first-year soil recovery of ^{15}N in the HV plots was about twice as much as AS (Table 4). However, the overall residual effect from the original ^{15}N was small for all N sources. Other studies have reported residual N uptakes from labeled HV residues by corn of 3% (Varco et al., 1989) and by irrigated oats (*Avena sativa* L.) of 2.5% (Cueto-Wong et al., 2001b). Similarly, residual ^{15}N uptakes from fertilizer have also been low, commonly ranging from 1 to 5% in tilled systems (Timmons and Baker, 1992; Timmons and Cruse, 1991; Janzen et al., 1990; Ladd and Amato, 1986). Therefore, labeled N recovered in the soil organic N pool is only slowly converted into crop available N; however, this fact also supports the corollary that labeled soil organic N is retained as a long-term soil N resource, albeit a slowly available N resource.

DISCUSSION

Recoveries of Labeled Ammonium Sulfate and Labeled Legume Residues

Only a few studies have compared the crop and soil recoveries of ^{15}N labeled AS fertilizer and ^{15}N labeled legume residues in upland (i.e., nonflooded) field experiments. In 1986, Ladd and Amato (1986) used 30-cm–diameter cylinders to study the recoveries of labeled AS and labeled medic (*Medicago littoralia* Rohde ex Lois.) residues into a wheat (*Triticum aestivum* L.) crop and into the soil, which was sampled to 90 cm. Ladd and Amato (1986) reported similar total recoveries (crop plus soil) for both sources, with the majority of the AS recovered in the plant and the majority of the medic residue N recovered in the soil. Janzen et al. (1990) conducted field-plot studies and reported that spring wheat N uptakes from ^{15}N-labeled flat pea (*Lathyrus tingitanus* L.) and lentil (*Lens culinaris* Medikus) res-

idues averaged 14% across three Canadian Prairie locations, whereas corresponding crop recoveries from AS averaged 25%. Janzen et al. (1990) sampled their soils to 120 cm and reported greater recoveries of legume residue N in the soil with about two thirds of the labeled soil N contained within the 0- to 15-cm layer of soil. Harris et al. (1994) studied the fate of ^{15}N-labeled red clover (*Trifolium pratense* L.) in Pennsylvania using 61-cm–diameter by 45-cm–deep cylinders and reported first-year recovery of labeled clover N in the soil of 66%, whereas corresponding values for AS were 23%.

Our first-year recoveries of labeled N in the crop, the soil, and the total recoveries are in agreement with results from the previously mentioned labeled AS vs. labeled legume residue studies (Table 6). Table 6 shows a general consensus among upland field studies, which span a wide range of soils and climates, that about twice as much labeled AS is recovered by first-year crops (average of 33%) compared with the crop N recoveries from labeled legume residues (average of 15%). Conversely, about twice as much of the labeled N from legume residues is recovered in the soil (average of 55%) compared with AS (average of 27%), with virtually all the soil-labeled N recovered in the organic N fraction. The general results from the upland field studies of Table 6 have been observed in other experimental conditions. For example, Westcott and Mikkelsen (1987) grew flooded rice (*Oryza sativa* L.) in field microplots and reported that rice recovered 24% of the ^{15}N from AS and 10% from labeled HV, with the soil recovering 26% of the AS ^{15}N and 35% of the HV ^{15}N. Similarly, a 10-wk greenhouse pot study (Corak et al., 1992) with perennial ryegrass (*Lolium perenne* L.) reported average plant uptakes of 51% from labeled AS compared with 29% from labeled HV residues, whereas soil and root recoveries were 31% for AS and 57% from HV. Azam et al. (1985) also conducted a short 5-wk greenhouse pot study with corn and found 20% of the ^{15}N from AS in the tops and roots compared with only 5% of the ^{15}N from labeled Sesbania (*Sesbania aculeata* L.) residues, whereas the soil contained 41% of the labeled AS and 89% of the labeled Sesbania ^{15}N. Thus, there is a consistent agreement covering a wide range of field studies and greenhouse studies that about twice as much labeled AS is recovered by first-year crops compared with the crop N recoveries from labeled legume residues, with the soil organic N recovering about twice as much N from legume residues as from AS.

The reasons for the greater recoveries of legume residue ^{15}N in the soil organic N are complex. The two most common explanations are (i) that a portion of the residues are resistant to decomposition and (ii) that a portion of the decomposed N is recovered as organic N associated with soil biomass or other organic compounds produced during residue decomposition (Varco et al., 1993; Harris et al., 1994; Azam et al., 1985). For example, Harris et al. (1994) traced the ^{15}N from red clover residues and from AS into several soil N pools and at the end of the first season found that (i) the inorganic N pool contained less than 5% of the ^{15}N for each source, (ii) that the soil microbial biomass con-

Table 6. Summary of the recoveries of ^{15}N, as a percentage of applied ^{15}N, for first-year crop after additions of ammonium sulfate (AS) or legume residues for upland field studies involving direct comparisons of labeled AS with labeled legume residues.

Literature source	Ammonium sulfate			Legume residues			Growing season precip.	Annual crop, legume residue crop, N conc. in legume, soil texture, location
	Plant	Soil	Total	Plant	Soil	Total		
Seo et al., this study	32	15	47	15	38	54	849	corn, hairy vetch (34 g N kg^{-1}), loam, Korea
Ladd and Amato, 1986	50	34	84	17	67	84	281	wheat, medic (32 g N kg^{-1}), sandy loam, Australia
Janzen et al., 1990†	34	36	70	20	61	81	326	wheat, lentil (33 g N kg^{-1}) and flat pea (35 g N kg^{-1}), sandy loam, Western Canada
Janzen et al., 1990†	21	25	46	10	49	59	460	wheat, lentil (33 g N kg^{-1}) and flat pea (35 g N kg^{-1}), loam, Western Canada
Janzen et al., 1990†	21	31	52	14	49	63	355	wheat, lentil (33 g N kg^{-1}) and flat pea (35 g N kg^{-1}), silt loam, Western Canada
Harris et al., 1994	39	23	62	16	66	82	375	corn, red clover (31 g N kg^{-1}), silt loam, Pennsylvania
Avg. across all studies	33	27	60	15	55	70		

† Data are average recoveries for the first crop after ammonium sulfate, or lentil and flat pea residues, for 2 crop-years at each location.

tained higher quantities of ^{15}N from clover residues (18%) than AS (5%), and (iii) that most of the soil ^{15}N resided in the soil organic N components with higher quantities from clover residues (44%) than from AS (14%). Varco et al. (1993) periodically sampled field-incubated soil cores over 11 wk that contained ^{15}N-labeled HV residues or fertilizer N and concluded that a larger portion of HV ^{15}N was incorporated into soil organic N due to greater immobilization. Azam et al. (1985) conducted a greenhouse pot experiment with corn receiving ^{15}N-labeled Sesbania residues or labeled AS and after 5 wk recovered more labeled N in the soil biomass from Sesbania (10%) than AS (2%) and more labeled N in the humic acid fractions of the soil treated with Sesbania (40%) than the AS (13%). The soil data collected in our study are insufficient to determine the cause of the greater recovery of HV ^{15}N in soil organic forms, but the literature supports the proposition that it results from a combination of ^{15}N contained in unde-composed residues plus ^{15}N in compounds produced by the greater microbial activity involved in decomposing labeled N sources that contain C and N.

The total recovery (plant plus soil) of labeled N from field experiments comparing AS and labeled legume residues (Table 6) was greater for the legume residues in five of the six studies, but these differences were statistically significant in only about one half of the studies. Table 6 also shows differences in total N recoveries among the studies that range from about 50 to about 85% and therefore differences in unaccounted-for N losses. These differences in total recoveries can likely be attributed to the differences in growing season precipitation and soil texture, with higher losses occurring in the high rainfall summer climate of Korea than in drier climates (Table 6). Greater losses of N would be expected in higher rainfall conditions because water is a major factor driving nitrate leaching and denitrification.

Nitrogen Management Strategies for Crop Production and Maintaining Soil Nitrogen

The results of this study and the outcomes from other studies spanning a range of soils and climates (Table 6)

show that the fate of the N inputs from inorganic fertilizer are most likely to result in crop N uptake, whereas N from legume residues is most likely to reside in soil organic N. A sustainable N management system should perform the combined functions of supplying adequate N to the crop and improving soil quality by conserving soil organic N and sequestering N and C. The hypothesis has been advanced (Janzen et al., 1990; Ladd et al., 1981) that legume residues can contribute to long-term soil fertility through a buildup of soil organic N and thus produce a more sustainable long-term production system. For example, Ladd et al. (1981) reported that about 75% of the ^{15}N from labeled legume residues resided in the soil organic N after 1 yr, and after eight seasons about 35% remained in forms of soil organic N (Ladd et al., 1985). Our results (Fig. 2) show that a system that uses inorganic N to supplement N from HV cover-crop residues can meet crop N needs and conserve soil N, and should thus contribute to a more sustainable N management system than a system that relies solely on fertilizer N or legume residues.

Determining the optimum combination of fertilizer N and cover-crop N for sustaining crop production and conserving soil N depends on a range of site-specific factors. Some of these factors are the amount of cover crop growth, the N and C concentration in the residues, the method of soil incorporation, fertilizer timing, soil properties, climate, and the N removed in harvested crops. Nevertheless, the benefits of supplying N through a combination of inorganic and organic N sources merits further study and should contribute to developing more sustainable agricultural systems.

CONCLUSIONS

This study evaluated three pre-plant N management strategies for silage corn grown in a summer monsoon climate by measuring the recovery of labeled N from pre-plant AS, pre-plant HV residues, and labeled SD AS over 2 yr. The recovery of labeled N in the first-year corn was 32% for planting-applied AS, 15% of planting-applied HV residues, and 46% of the sidedress AS. After harvest, soil samples taken to 15 cm showed

negligible levels of inorganic N, with virtually all of the ^{15}N contained in the soil organic N. The soil contained more labeled N from the HV residues (38%) compared with about 15% from planting AS or sidedress AS. Total recoveries of labeled N in crop plus soil were 47% for planting AS, 54% for HV residues, and 60% for sidedress AS. The crop availability of the residual labeled N during the second year of the study was small, amounting to only about 2 to 4% of the original ^{15}N applied; thus, the majority of the first-year residual ^{15}N remained in the soil organic N pool. These results are consistent with other field studies conducted over a wide range of soil and climatic conditions that compared labeled AS with labeled legume residues and show that AS is about twice as effective as legume residues in supplying N to a crop, whereas legume residues contribute about twice as much N to the soil. This study demonstrates that a corn N management system using fertilizer N and legume cover-crop residues can meet both crop N requirements and conserve soil N, although the optimum mixture of fertilizer N and legume N depends on site-specific factors of individual production systems.

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